Model of Temperature Dependence Shape of Ytterbium -doped Fiber Amplifier Operating at 915 nm Pumping Configuration

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***Abstract*— We numerically analyze the temperature dependence of an ytterbium-doped fiber amplifier (YDFA) operating at 915 nm, investigating its gain and Noise Figure properties variation with temperature. The temperature-dependent gain and noise figure variation with YDFA length are numerically obtained for the temperature range of +20 ^{0}C to +70 ^{0}C. The results show that good intrinsic output stability against temperature change can be achieved in ytterbium doped fiber amplifiers even when operating at high gain regime with small signal input. This result demonstrates the great potential for stable high power laser communication systems based on ytterbium system.**

Keywords- YDFA; Gain; Noise Figure.

I. INTRODUCTION

Fiber lasers and amplifiers have attracted great interest recently, because they offer the advantages of compact size, high gain, guided mode propagation, better stability and their outstanding thermo-optical properties [1-4]. Ytterbium (Yb^{3+}) -doped fiber Amplifier (YDFA) has a great potential because it does not have some of the drawbacks associated with erbium-doped amplifier: excited state absorption phenomenon that can reduce the pump efficiency and concentration quenching by interionic energy transfer do not occur, and high doping levels are possible. Thus, it offers high output power (or gain) with a smaller fiber length. YDFA's have a simple energy level structure and provide amplification over a broad wavelength range from 975 to 1200 nm. Moreover, YDFA's can offer high output power and excellent power conversion efficiency [1,5-12].

YDFA's have great potential in many applications, including power amplification, sensing applications, free-space laser communications, and chirped-pulse amplification of ultra-short pulses [1,12-14].

This paper explores the effects of temperature on amplifier performance. For an amplifier, the temperature affects relative extraction by the signal and ASE. Thermal management is a critical issue and cannot be ignored. Some papers about temperature effect of Er^{3+}-doped fiber laser and amplifier were reported [15-17]. Temperature can affect the absorption and emission cross sections [2]. This paper demonstrates output characteristics of Yb^{3+}-doped fiber laser at different temperatures degrees. So from this research the temperature can affect the gain and noise figure (NF) at different length.

Established methods of modeling erbium amplifiers can be used to model ytterbium system [11,18-19]. However, modeling temperature sensitivity is completely different. The small energy gaps in the relevant stark levels in erbium systems, makes the determination of distinct sub-transition characteristics quite difficult [17], while this is not true in ytterbium system. Accurate characterization of Yb^{3+} absorption and emission cross sections is crucial [20,21].

II. THEORETICAL MODEL

We used standard rate equations for two-level systems to describe the gain and propagation characteristics of the Yb-doped fiber amplifier operating at 975 nm because the ASE power is negligible for a high power amplifier with sufficient input signal (about 1 mW). After the overlap factors are introduced and the fiber loss ignored, the simplified two-level rate equations and propagation equations are given as follows [12]:

$$\frac{dN_2(z,t)}{dt} = \frac{\Gamma_s P_s}{Ah\upsilon_s}[N_1\sigma_{sa} - N_2\sigma_{se}] + \frac{\Gamma_p P_p}{Ah\upsilon_p}[N_1\sigma_{pa} - N_2\sigma_{pe}] - \frac{N_2}{\tau} \quad (1)$$

$$N_1(z,t) - N_2(z,t) = N_0 \quad (2)$$

$$\frac{dP_s(z)}{dz} = P_s\Gamma_s[N_2(z,t)\sigma_{se} - N_1(z,t)\sigma_{sa}] \quad (3)$$

$$\frac{dP_p(z)}{dz} = P_p\Gamma_p[N_2(z,t)\sigma_{pe} - N_1(z,t)\sigma_{pa}] \quad (4)$$

Here, N_0 is the Yb-dopant concentration, N_1 and N_2 are the ground and upper-level populations. Γ_s and Γ_p are the oveperlapping factor between the pump (signal) and the fiber-doped area. $P_s(z,t)$, $P_p(z,t)$ are the signal and pump power respectively. σ_{sa} *and* σ_{se} are the signal absorption and emission cross sections. σ_{pa} *and* σ_{pe} are the signal absorption and emission cross sections. υ_s and υ_p are the frequencies of signal and pump light, respectively. A is the doped area of the fiber. τ is the upper state lifetime.

Under the condition of the steady state regime, where all of the level population are time invariant i.e., $\frac{dN_i(z,t)}{dt} = 0 \ \ (i = 1,\ 2)$,

$$\frac{N_2}{\tau} = \frac{\Gamma_s P_s}{Ah\upsilon_s}[N_1\sigma_{sa} - N_2\sigma_{se}] + \frac{\Gamma_p P_p}{Ah\upsilon_p}[N_1\sigma_{pa} - N_2\sigma_{pe}] \quad (5)$$

$$N_1(z,t) = N_0(z,t) - N_2(z,t) \quad (6)$$

A. Spectroscopy of ytterbium in silica

Ytterbium in silica is a simple, two level system having four Stark levels in the lower manifold $F_{7/2}$ and three Stark levels in upper manifold $F_{5/2}$. An energy level diagram specific to Nufern 5/125 fiber is shown in Figure 1 [22]. Because the splitting of the levels depends on the glass composition, concentration of dopants and co-dopants, and the degree of structure disorder of the glass network, the energy level diagram for Yb in silica may vary with each individual fiber. The absorption and emission cross-sections for Yb in silica are related to the temperature and the energy of the levels by the following relationships:

Level	Energy [cm-1]
a	0
b	492
c	970
d	1365
e	10239
f	10909
g	11689

[16]

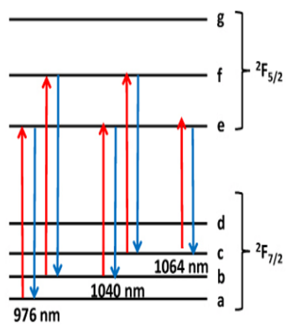

Figure 1: Energy level diagram of Yb in silica with 976 nm, 1040 nm, and 1064 nm transitions labeled [22].

$$\sigma_{sa}(\upsilon,T) = \sum_{x=a}^{d}\sum_{y=e}^{g}\frac{e^{-\frac{E_x}{KT}}}{\sum_{x=a}^{d} e^{-\frac{E_x}{KT}}}\ \sigma_{xy}^{sa}(\upsilon) \quad (7)$$

$$\sigma_{se}(\upsilon,T) = \sum_{x=e}^{g}\sum_{y=a}^{d}\frac{e^{-\frac{E_x}{KT}}}{\sum_{x=e}^{g} e^{-\frac{E_x}{KT}}}\ \sigma_{xy}^{se}(\upsilon) \quad (8)$$

where E_x are the energies of the level difference between level x and a, when $x \in (a,d)$ where a is the ground state in lower manifold and the energies of the level difference between levels x and e, in the ground state in upper manifold when $x \in (e,g)$, T is the temperature, K=$1.3806 \times 10^{-23} J/k$ is Boltzmann's constant, and $\sigma_{xy}^{sa}(\upsilon)$ and $\sigma_{xy}^{se}(\upsilon)$ are the absorption and emission cross-sections of the sub-transitions [17]. To be able to calculated σ_{se}, it needed to use McCumber theory [23] in the Yb system, this expressed as

$$\sigma_{se}(\upsilon,T) = \sigma_{sa} e^{(\varepsilon - h\upsilon)/KT} \quad (9)$$

where $e^{\varepsilon/KT} = e^{Eea/KT}\frac{1+e^{-E_{ba}/KT}+e^{E_{ca}/KT}+e^{E_{da}/KT}}{1+e^{-E_{fe}/KT}+e^{E_{ge}/KT}}$, $E_{xy} = E_x - E_y$ (10)

And h=6.626 x 10^{-34} J.s. is Planck constant and ε is an active energy and given by

$$\frac{N_1}{N_2} = \exp(\varepsilon / KT) \quad (11)$$

Where N_1 and N_2 *are* Yb doping concentration at the upper and lower energy levels, respectively. Using the absorption and emission cross section from Eqs.(7-11), and the propagation equations (3) and (4) can even be solved analytically in this case [23].

The small signal gain G for active length of the fiber L can be given by

$$G(\lambda) = \exp\left[\Gamma_s(N_2(z,t)\sigma_{se} - N_1(z,t)\sigma_{sa})L\right] \quad (12)$$

Figure 2 and 3 show the variation of Yb absorption and emission cross sections at various temperatures respectively [21]. It is clear from figure 3 that the signal absorption cross section declines with increasing wavelength and it is almost 0 at 1064 nm. The term $N_1(z,t)\sigma_{sa}$ can be ignored as it is a decreasing function of signal wavelength, then

$$G(dB) = 10\log_{10}\exp\left[\Gamma_s N_2 \sigma_{se} L\right] \quad (13)$$

The amplified spontaneous emission (ASE) noise spectrum uses the noise figure (NF) given or as input parameter. In the practical case the *ASE* is presented at input of the doped fiber, therefore the amplified input *ASE* P_{ASE}^i spectral density can be added to the amplified output *ASE* spectral density P_{ASE}^o, so

$$P_{ASE}^o = P_{amp} + P_{ASE}^i \ G \quad (14)$$

Where G is the gain and P_{amp} is the spectral density of ASE generated by the doped fiber. For input ASE gives the signal spontaneous beat noise (*1/G*) limited noise figure as a function of the signal gain and input and output ASE spectral densities therefore the NF can be expressed as:

$$NF = \frac{1}{G} + \frac{P_{ASE}^o(\lambda_s)}{Gh\upsilon_s} - \frac{P_{ASE}^i(\lambda_s)}{h\upsilon_s} \quad (15)$$

Where 1/G is the beat noise, $P_{ASE}^o(\lambda_s)$ is the output ASE spectral density (Watt/Hertz) at signal wavelength, $P_{ASE}^i(\lambda_s)$ is the input ASE spectral density at signal wavelength, and υ_s is the frequency of the signal wavelength. For lower gains, a much simpler model which ignores the effect of ASE on the level populations can be used, so the $P_{ASE}^i(\lambda_s) = 0$.

For each signal wavelength the noise figure can be calculated in decibel (dB) and is given by:

$$NF(dB) = 10 \ \log_{10}\left(\frac{1}{G} + \frac{P^{o}_{ASE}(\lambda_s)}{Gh\upsilon_s}\right) \quad (16)$$

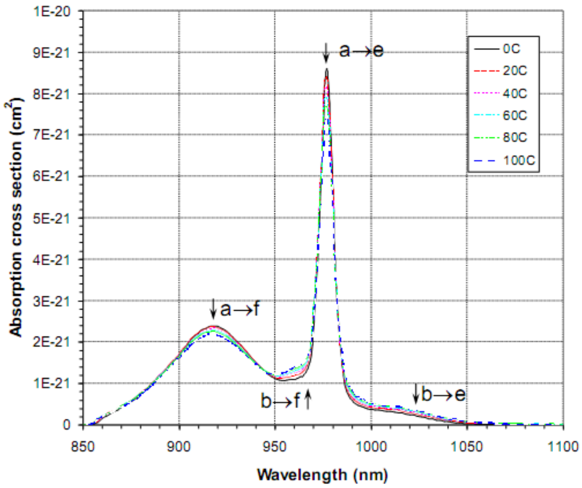

Figure 2: Yb absorption cross sections at various temperatures. [18]

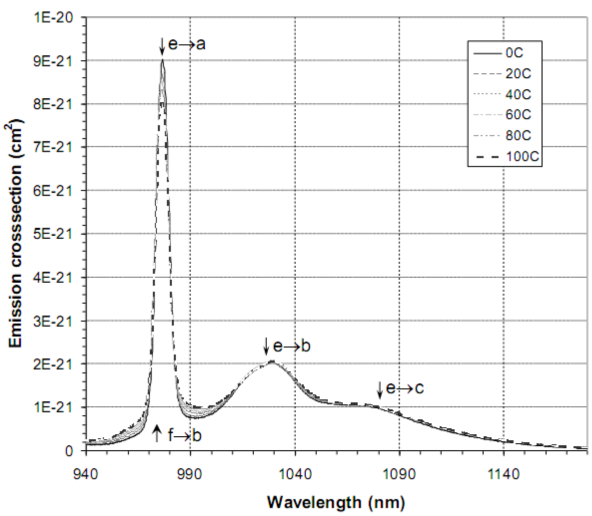

Figure 3: Yb emission cross sections at various temperatures [21].

III. RESULTS AND DISSCUSSIONS

For numerical calculation, the fiber parameters for YDFA amplifier are shown in Table 1. We studied the variation of gain and NF with the length of the amplifier over the temperature range from 20 °C to 70 °C at signal wavelength of 1064 nm. The results are shown in Figures 4 and 5, respectively. It is clear from the results that the signal gain raises with increases in the length, at the same time the gain declines when the temperature increases. However the NF increases when the temperature rises. Furthermore the NF increases with increasing the length. It is clear from the results that the variation of the NF with temperature is minimal for lengths over 5 *m*.

IV. CONCLUSION

A YDFA model has been introduced including the temperature effects for gain and noise figure of a length of the YDFA amplifier. The temperature dependence of the gain and noise figure on various temperatures was taken into consideration which shows that the performance of YDFA exhibit excellent low temperature sensitivity. The analytical solution of the propagation equations has also been derived for the temperature range from 20 °C, to +70 °C for finding the gain. These results demonstrate that highly stable ytterbium doped fiber amplifiers can potentially be achieved.

Table 1: The fiber parameters and symbols used in the numerical calculations [18]

Symbol	Definitions	Value
σ_{sa}	Signal absorption cross sections	$2.3\times10^{-27}\,m^2$
σ_{se}	Signal emission cross sections	$1.09\times10^{-27}\,m^2$
υ_s	Frequency of input signal	$3.279\times10^{14}\,Hz$
υ_p	Frequency of pump signal	$2.819\times10^{14}\,Hz$
λ_s	Signal Wavelength	$1064nm$
λ_p	Pump wavelength	$915nm$
τ	The upper state lifetime	$0.84\ ms$
N_0	Yb-dopant concentration	$3.35\times10^{25}\,m^{-3}$
A	Doped area of the fiber	$7.8\times10^{-11}\,m^2$
Γ_s	Oveperlapping factor between the signal and the fiber-doped area	0.6
Γ_p	Oveperlapping factor between the pump and the fiber-doped area	0.01
P_p	Input Pump power of 20 °C and 70 °C	$10\ \mu W$ to $10\ W$
$P^{i}_{ASE}(L=0)$	Amplified input power of *ASE*	0
L	Length of the fiber	0 to $7m$

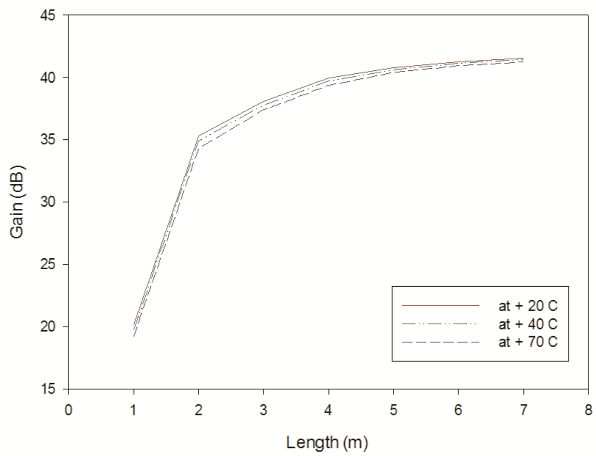

Figure 4: The change of the signal gain with temperature and length.

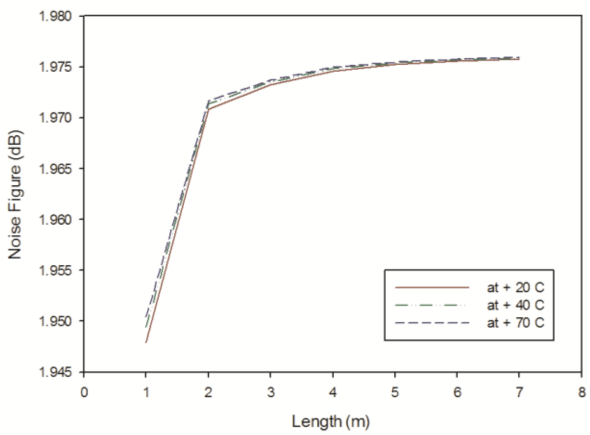

Figure 5: The change of the Noise Figure with temperature and length.

REFERENCES

[1] R¨udiger Paschotta, Johan Nilsson, Anne C. Tropper, and David C. Hanna, Ytterbium-Doped Fiber Amplifiers, IEEE JOURNAL OF QUANTUM ELECTRONICS, vol. 33, no. 7, JULY 1997.

[2] J. Chen, Z. Sui, F. Chen and J. Wang, Output characteristics of Yb^{3+}-doped fiber laser at different temperatures, vol. 4, no. 3, Chin. Opt. Lett. (2006).

[3] D. Xue, Q. Lou, J. Zhou, L. Kony, J. Li, Chin. Opt. Lett. 3,345 (2005).

[4] M.J.F. Digonnet, "Rare-Earth-Doped Fiber Lasers and Amplifiers model for rare-earth-doped fiber amplifiers and lasers," CRC Press; 2nd edition (2001).

[5] H. M. Pask, R.J. Carman, D. C. Hanna, A. C. Tropper, C. J. Mackechinc, P. R. Barber, and J. M. Dawes, IEEE Sel. Top. Quantum Electron. 1, 2 (1995).

[6] D. C. Hanna, R. M. Percival, I. R. Perry, R. G. Smart, P. J. Suni, J. E. Townsend, and A. C. Tropper, "Continuous-wave oscillation of a monomode ytterbium-doped fiber laser," *Electron. Lett.*, vol. 24, pp.1111–1113, (1988).

[7] D. C. Hanna, R. M. Percival, I. R. Perry, R. G. Smart, P. J. Suni, and A. C. Tropper, "An ytterbium-doped monomode fiber laser: broadband tunable operation from 1.010 _m to 1.162 _m and three-level operation at 974 nm," *J. Mod. Opt*., vol. 37, pp. 517–525, (1990).

[8] J. C. Mackechnie, W. L. Barnes, D. C. Hanna, and J. E. Townsend, "High power ytterbium (Yb3+)-doped fiber laser operating in the 1.12 _m region," *Electron. Lett.*, vol. 29, pp. 52–53, (1993).

[9] J. Y. Allain, M. Monerie, H. Poignant, and T. Georges, "High-efficiency ytterbium-doped fluoride fiber laser," *J. Non-Crystalline Solids*, vol. 161, pp. 270–273, (1993).

[10] S. Magne, M. Druetta, J. P. Goure, J. C. Thevenin, P. Ferdinand, and G. Monnom, "An ytterbium-doped monomode fiber laser: amplified spontaneous emission, modeling of the gain and tunability in an external cavity," *J. Lumin*., vol. 60, pp. 647–650, (1994).

[11] H. M. Pask, R. J. Carman, D. C. Hanna, A. C. Tropper, C. J. Mackechnie, P. R. arber, and J. M. Dawes, "Ytterbium-doped silica fiber lasers: versatile sources for the 1–1.2 _m region," *IEEE J. Select. Topics Quantum Electron.*, vol. 1, pp. 2–13, (1995).

[12] Liu Yan_, Wang Chunyu, Lu Yutian, A four-passed ytterbium-doped fiber amplifier, Optics & Laser Technology, pp. 1111-1114 39 (2007).

[13] R. Paschotta, D. C. Hanna, P. DeNatale, G. Modugno, M. Inguscio, and P. Laporta, "Power amplifier for 1083 nm using ytterbium doped fiber," *Opt. Commun.*, vol. 136, pp. 243–246, (1997).

[14] V. Cautaerts, D. J. Richardson, R. Paschotta, and D. C. Hanna, "Stretched pulse Yb3+: silica fiber laser," *Opt. Lett.*, vol. 22, no. 5, pp. 316-318 (1997).

[15] N. Kagi, A. Oyobe, and K. Nakamura, J. Lightwave Technol. 9, 261 (1991).

[16] H. Tobbon, Electron. Lett. 29, 667 (1993).

[17] M. Bolshtyansky, P. Wysocki and N. Conti, "Model of temperature dependence for gain shape of erbium-doped fiber amplifier", Journal of Lightwave Technology, vol.18, 1533-1540 (2000).

[18] C.R. Giles, E. Desurvire, "Modeling erbium-doped fiber amplifiers," J. Lightwave Technol., vol. 19, no. 7, pp. 271 – 283, (1991).

[19] Yu. A. Varaksa, G. V. Sinitsyn, and M. A. Khodasevich, "Modeling the gain and amplified spontaneous emission spectra of erbium-doped fiber amplifiers," *J. Appl. Spectrosc.*, vol. 73, no. 2, pp. 309–312, (2006).

[20] Xiang Peng, Joseph McLaughlin and Liang Dong, "Temperature Dependence of Ytterbium Doped Fiber Amplifiers", Conference Paper Optical Amplifiers and Their Applications (OAA) Budapest, Hungary, August 7, (2005).

[21] Xiang Peng and Liang Dong, "Temperature dependence of ytterbium-doped fiber amplifiers", J.Opt.Soc. Am. B, Vol. 25, Issue 1, pp. 126-130 (2008).

[22] Leanne J. Henry, Thomas M. Shay, Dane W. Hult and Ken B. Rowland Jr "Thermal effects in narrow linewidth single and two tone fiber lasers", vol. 19, no. 7 Optics express 6165 (2011)

[23] C. Barnard, P. Myslinski, J. Chrostowski, and M. Kavehrad, "Analytical model for rare-earth-doped fiber amplifiers and lasers," IEEE J. Quantum Electron., vol. 30, pp. 1817–1830, (1994).